Cost and Reliability Study for a Large Array of Small Reflector Antennas for JPL/NASA Deep Space Network (DSN)

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ABSTRACT

A study is performed to estimate the cost of an array of small aperture reflector antennas to be used instead or in conjunction with the current large reflector antennas of the JPL/NASA Deep Space Network (DSN), for servicing present and future NASA missions which involve smaller spacecraft with limited power and smaller, lower gain antennas. The advantages of the array configuration in terms of cost and reliability are studied A probabilistic determination of the reliability and availability of the array as a function of the number of array elements and the availability of individual array elements is made. The impact of additional marginal elements on the operational availability of the array is studied. Parametric cost and reliability plots are presented and directions for further investigation are outlined

I. INTRODUCTION

The Jet Propulsion Laboratory is currently engaged in a study to develop a quantitative understanding of the performance, cost, and technical risks associated with using a large array of small aperture reflector antennas for Deep Space Network (DSN) applications [l-**2].** The array will be a receive-oniy system, operating simultaneously at S- and X-bands. The product of the study will bean analytic model that relates the total systems cost to the diameter of the elemental apertures for a given G/T (i.e., gain divided by system temperature).

The cost of the entire array is parametrized as a function of the antenna element diameter for a given figure of merit, G/T, for the entire system. As a benchmark, the prescribed G/T would be that of from one to three of the existing NASA/JPL Deep Space Network 70m reflector antennas. Costs for the entire system is modeled during the study. These include the antennas, radio and intermediate frequency amplification, signal distribution, combiner electronics, and monitoring and controlling system needed to operate the array in a synchronous fashion. However, oniy costs related to the antenna optics (feed, reflector, and subreflector) are discussed in this paper.

In one scenario, four 70-meter antennas arrayed together will provide 6 dB more link capability than currently exists. This implies 3 additional 70 meter antennas. The 6-dB more G/T will be competitive with what is expected to be gained by moving to a Ka-band frequency system on a single 70-meter antenna. This additional G/T would be practical for serving the current version of the Galileo S-band mission and save problems and expenses involved in arraying with non-DSN antennas. With sufficient G/T on the ground, both the DSN as well as future missions could postpone Ka-band development, and thereby save development resources. All existing deep space spacecraft. are either S- or X-band or both. Even the Pioneer 10 and 11 as well as the Voyager spacecraft could be serviced for many years into the future.

Arraying with existing DSN antennas not only enhances the overall G/T but also provides two-way capability. One third of such an array coupled with and 80 kW transmit from each 34 meter antenna would be the functional equivalent of a 70-meter antenna. Furthermore, by operating as independent smaller apertures, an array offers scheduling flexibility. All or part of the array can be concentrated for a single weak source (e.g. Galileo) or assigned independent targets (e.g. Lunar Rovers, Mars rovers, etc.).

Other future missions include multiple rovers or orbiters around or on the moon and Mars. By using high-power transmission and large collecting aperture for reception on Earth, we could employ very simple and low power communication facilities on the rovers.

Current technology makes it possible to transmit high power from a single antenna (e.g., up to one megawatt). On the other hand, deep space missions are often power limited and with the new emphasis **on** smaller cheaper "micro spacecraft", as little power as possible **will** be allocated to the communication link. Also, the arraying of transmitting antennas involves more technological risk than that of the receiving antennas. This suggests a ground station configuration of a single parabolic antenna for uplink together with a much larger collecting area for receiving weak spacecraft signals.

Thus, in another scenario, the system to be modeled will consist of a single 34m-class antenna having both uplink and downlink capabilities (e. g., using the new 34m beam waveguide (BWG) reflector of the JPL DSN as a model), arrayed with a number of receive only antennas having diameters less than 34 meters.

Figure 1. presents a typical system block diagram for a large array of reflector antennas. Notice that the IF stages can be either localized at each antenna, or be centralized at the location where correlation/combining takes place, by bringing the amplified RF signals to this central location.

II. NUMBER OF ARRAY ELEMENTS

The number of antennas needed to synthesize the G/T of a 70m antenna is a function of the antenna diameter and system noise temperature. Shown in Table 1 is the range of the number of antennas needed for the eight(8) diameters considered in this study. This range allows both the cooled and uncooled amplifiers to be parametrized, as well as a range of G/T equivalent to one to three 70-meter antennas.

Table 1. The Range of Number of Array Elements Under Consideration

Reflector Diameter in meters	Number of Reflector Units	
	Minimum	Maximum
3	545	27000
5	196	10000
10	49	2500
15	22	1100
20	12	615
25	8	394
30	5	274
35	4	201

III. OPTICS OF ARRAY ELEMENTS

The antenna optics are broken into two regimes. For *small* reflector diameter antennas, a frequency selective subreflector is used to separate S-band, Arranged as a prime focus system, from X-band, arranged as a Cassegrain system. For large diameter antennas, both bands operate in a Cassegrain arrangement, with the bands separated by either a dual frequency (concentric) feed, or a frequency selective surface (FSS) diplexer. The transition from optics arrangement to the other will occur in the range of 10-20 meter diameter antennas.

IV. REFLECTOR ANTENNA COST

It should be noted that the reflector antenna costs presented here, unless specifically stated otherwise, do not include the cost of the radio and intermediate frequency amplification, signal distribution, combiner electronics, and monitoring and controlling system, etc. These other major components are presently and concurrently under study and must be taken into account for overall system costing, Figure 2 presents a graph of cost versus antenna size (reflector diameter) for several different existing or under-development antenna systems. For the most part, they follow a specific curve, such that the cost C of a ground station reflector antenna as a function of its diameter D can be estimated as proportional to

$$C \propto (D)^{\beta}, \quad \beta \approx 2.5 - 2.7 \qquad (1)$$

Reflector Antenna costs are broken into the following categories:

A) Structure
B) Main Reflector Surface
C) Axis Drive
D) Position Control
E) Foundation
F) Shipping and Installation
G) Feed System (including possible frequency selective surfaces)
H) Power Distribution on Site

Figure 3 shows how these various components vary as a function the antenna diameter. As can be seen, the cost of the structure is the dominating factor.

Presently, two contracts with the industry (TIW and Scientific Atlanta) are under way, in order to obtain more accurate and up-to-date cost estimates for various antenna size and requirements. These should significantly increase the accuracy of the cost models.

V. PROBABILISTIC AVAILABILITY OF AN ARRAY

The cost model for the array will help to optimize the required number of antenna elements for a given performance and the lowest possible cost. An important consideration, however, is the study and modeling of the reliability, or availability, of the array as a function of the number of array elements. This factor can significantly impact the overall cost of the antenna system.

The availability, or reliability of each element of the array is loosely defined here, as the percentage of time that the element is ready and available for use and operation, considering the down times required for maintenance, parts replacements, breakdowns, etc. The analysis, however, is applicable to any operational probability factor that applies to individual array elements, as well as the total array system performance. The only provision made is that the availability for each element is assumed to be equal to but independent of those for the other elements. No correlation is assumed among the failure rate or timing of different elements.

If the minimum required number of elements for successful operation (with no performance margin) is given as n, and if the independent availability factor for each element of the array is given as p (a number between O and 1, sometimes specified as a percentage), Then it is obvious that the availability of the array is simply given as:

$$P = p^{n}. \tag{2}$$

Thus for a given p, the availability of the array is substantially reduced as the number of array elements increases. As an example, for element availability of p = 0.9, the total array availability is reduced to $P = 0.59$ for $n = 5$ and $P = 0.12$ for $n = 20$. This drastic reduction can be explained by the fact that there is no safety margin for the operation, and that the breakdown of even one element results in system failure. By adding marginal elements, however, the situation can be substantially improved and indeed, the availability of the array can be increased to levels much higher than that of a single element.

A somewhat more detailed analysis of what follows is given in [3]. Let's assume that the minimum required array elements for successful operation is n, and that m marginal elements are added to the system so that the total number of array elements is n + m, out of which a minimum of n must be operational at any given time. In this case, the array success probability, or what we loosely define as the array availability is *given* by:

$$P = \sum_{k=0}^{m} C(n+m,k)(1-p)^k p^{n+m-k}. \tag{3}$$

-in which,

$$C(n+m,k) = (n+m)! / [(n+m-k)!\, k!], \tag{4}$$

is the number of combinations of k elements taken from a pooi of n + m elements. Equation (2) is a form of the cumulative **Bernoulli** or **binomial** probability distribution function [4]. It has many interesting properties as will be presented.

Equation (3) is applied to arrays of the same overall G/T, or assuming that T is more or less constant across the arrays, for the arrays of equal Gs or, equivalently, equal collecting apertures. Thus, for a total collecting aperture area of A, the individual element aperture of an array of n elements can be written as:

$$A_n = A / n. \tag{5}$$

For m marginal elements of aperture An, the increase in total collecting aperture is m An , and the percentage increase in the collecting area is **given** as:

$$m A_n / n A_n = m / n. \tag{6}$$

Therefore, in order to make a comparative assessment of the various arrays' performance, the number of marginal elements are given as a percentage of the minimum required array elements. In Figure 4, the array availability is plotted as function of the number of marginal elements as a percentage of the minimum array elements, for various minimum required array elements, and for a fixed element availability of $p = 0.9$.

Figure 5 provides a different and perhaps a more useful way of looking at the array availability distribution, For a given element availability, and for a desired array availability, the required percentage increase in number of elements is plotted as a function of the minimum number of array elements. As in the previous figure, the element availability factor is fixed at 0.9. Similar plots can be obtained for other element availability factors.

From the data provided in Figures 4-5, the following interesting observations can be made.

1) The availability of the array can be increased by increasing the number of marginal elements.

2) The array availability starts with a value much below the element availability, but increases rapidly and surpasses the element availability for a margin of less than about 30 percent or 1 dB.

3) The rate of increase is much faster for arrays with larger number of elements, even though it starts with a much smaller value.

4) At some point as the margin level increases, ail the arrays with different number of elements reach the same availability level, beyond which a given margin results in higher availability for larger arrays than for smaller arrays.

5) For larger arrays, the margin can be increased more gradually, since each additional element constitutes a smaller fraction of the total array. For an element availability of 0.9, for example, the minimum availability of a 2-element array is 0.81 which increases to 0.972 by the addition of one element, which is the smallest increment and constitutes a 50°/0 increase in the collecting area *or* a 1.76 dB margin. In contrast, for a 10 element array with the same element availability, the minimum array availability is 0.349, but by the addition of 3 elements (a 30% increase or a 1.1 dB margin, an array availability of 0.966 is achieved.

VI. TOTAL ARRAY COST

The cost of a reflector antenna (structure and feed only) was estimated by equation (l). Now consider two array systems with the same total collecting aperture A but two different number of elements n 1 and n2. The total cost of the array for the two cases can be written as:

$$C_{t1} \propto n1\, C_{n1} = n1\, (D_{n1})^{\beta} = n1\, (A_{n1})^{\beta/2}\ ,\ A_{n1} = A / n1 \tag{7}$$

$$C_{t2} \propto n1\, C_{n2} = n2\, (D_{n2})^{\beta} = n2\, (A_{n2})^{\beta/2},\ A_{n2} = A / n2 \tag{8}$$

Then the ratio of the cost for two arrays can be written as:

$$C_{t2} / C_{t1} = (n2/n1)^{-(\beta/2\ -1)} \approx (n2/n1)^{-0.3}\ ,\ \text{for } \beta \approx 2.6 \tag{9}$$

The ratio of the marginal cost increase, due to the increase in marginal array elements required for operation, can be similarly obtained as:

$$
\begin{aligned}
dC_{t2} / dC_{t1} &= (r2/r1)\,(C_{t2} / C_{t1}) = (r2/r1)\,(n2/n1)^{-(\beta/2-1)} \\
&\approx (r2/r1)\,(nZ/n\,1)^{-0.3}
\end{aligned}
\qquad (lo)
$$

in which r 1 and r2 are percentage margins of array elements required for the two cases.

Based on Equations (9-10), Figure 6 shows the variation of the total cost of the array (including the additional marginal elements), for a given element availability and a desired array availability, with the minimum required number of array elements. The cost of the arrays with no marginal elements is also presented as a reference. This figure clearly shows the cost advantage of the larger array systems. However, as already mentioned, these curve do not include RF/IF electronics and other components.

Figure 7 shows a preliminary plot of the total cost of the array system including the electronics (but with no marginal elements) as a function of individual antenna element diameter. This figure shows that at the smaller reflector end (larger arrays) the cost of the electronics predominates, while at the larger reflector end (smaller arrays) structural costs become dominant. Inclusion of marginal elements analysis in this total cost model, and the acquisition and inclusion of more accurate cost data are presently under way.

VI. CONCLUSION

This study has demonstrated some of the advantages of the selection of a large array of , smaller apertures in comparison with a small (few elements) array, in terms of providing a more graceful way of increasing the performance margin, and conversely, a more graceful degradation in case of element failure. Furthermore, the fact that for a given margin or percentage increase in the collecting aperture, a higher array availability is achieved in arrays with larger number of elements, can be used in trading-off element reliability in larger arrays for *cost,* while still maintaining the same overall reliability as that of an array with a smaller number of elements with higher individual reliability. Interestingly enough, the smaller elements used in larger arrays typically have a much larger reliability than their larger counterparts to start with, since they are typically less complex and easier to maintain, Further study is needed and is presently under way to reach a detailed and more accurate cost model which takes these questions into account, in a rigorous and satisfactory manner.

ACKNOWLEDGMENT

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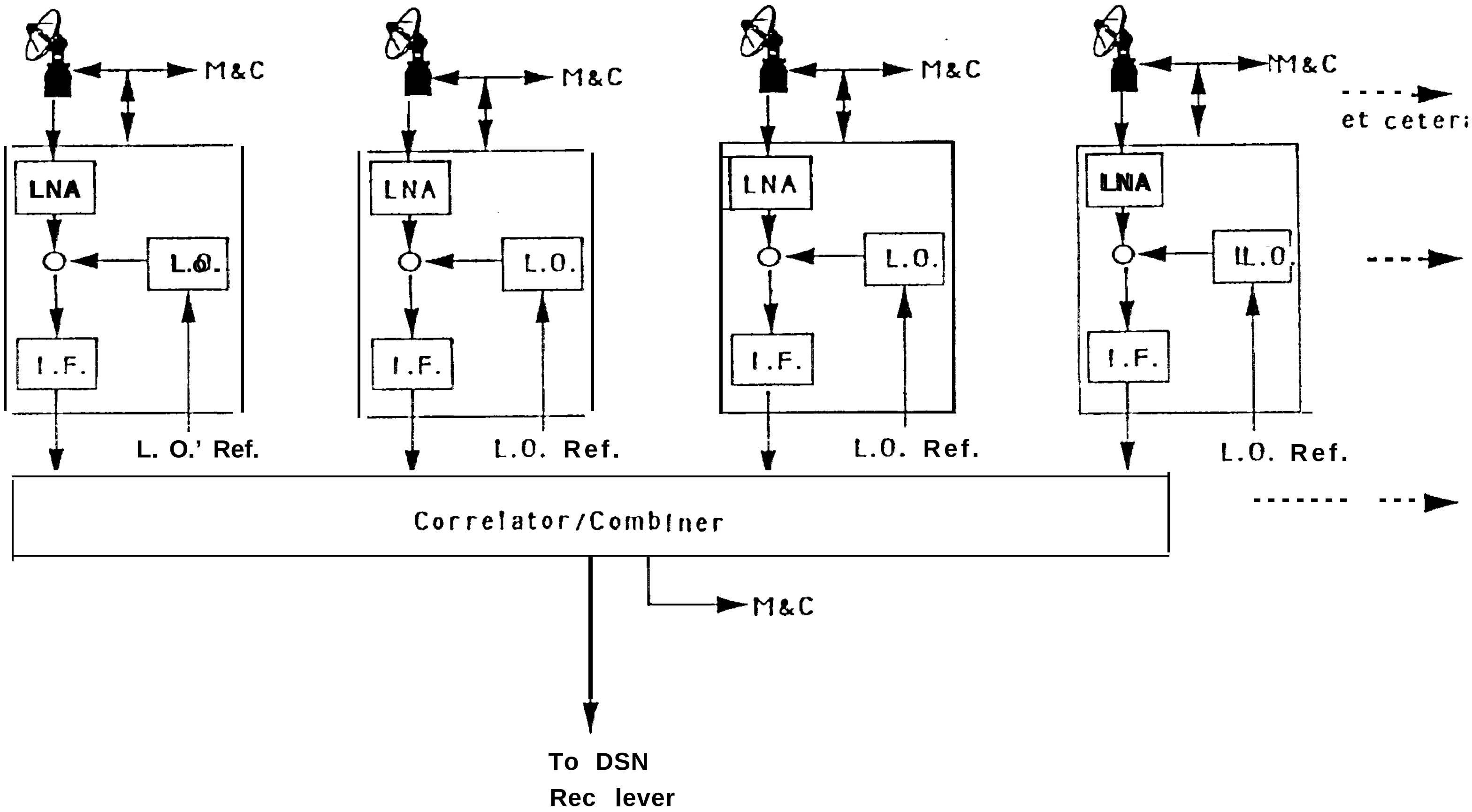
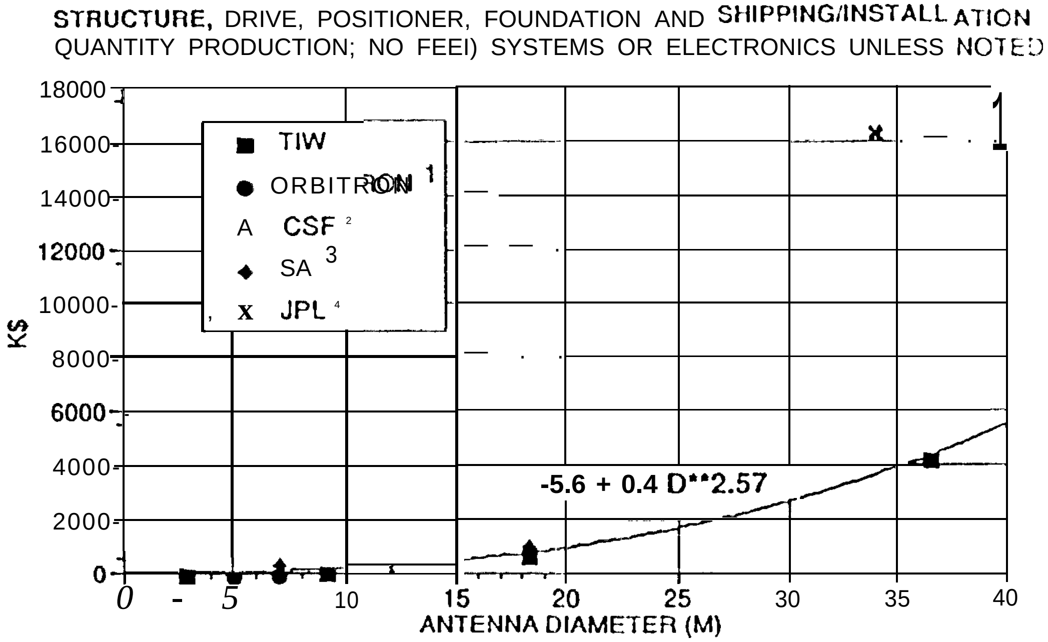


Figure 1. System Block Diagram for a Large Array of Reflector Antennas



1) No shipping Installation
2) Price for 100 units/100; Radio Schmidt Telescope Study; 25 GHz upper frequency
3) Single unit price (no quantity production); Non-tracking S-band and X-band high performance feeds included
4) JPL Interoffice Memorandum 3330 -90- 116--> Array of 34m BWG Antennas; CofF Budget/4; 32 GHz upper frequency

Figure 2. Cost of Typical Reflector Antenna systems as a Function of Diameter

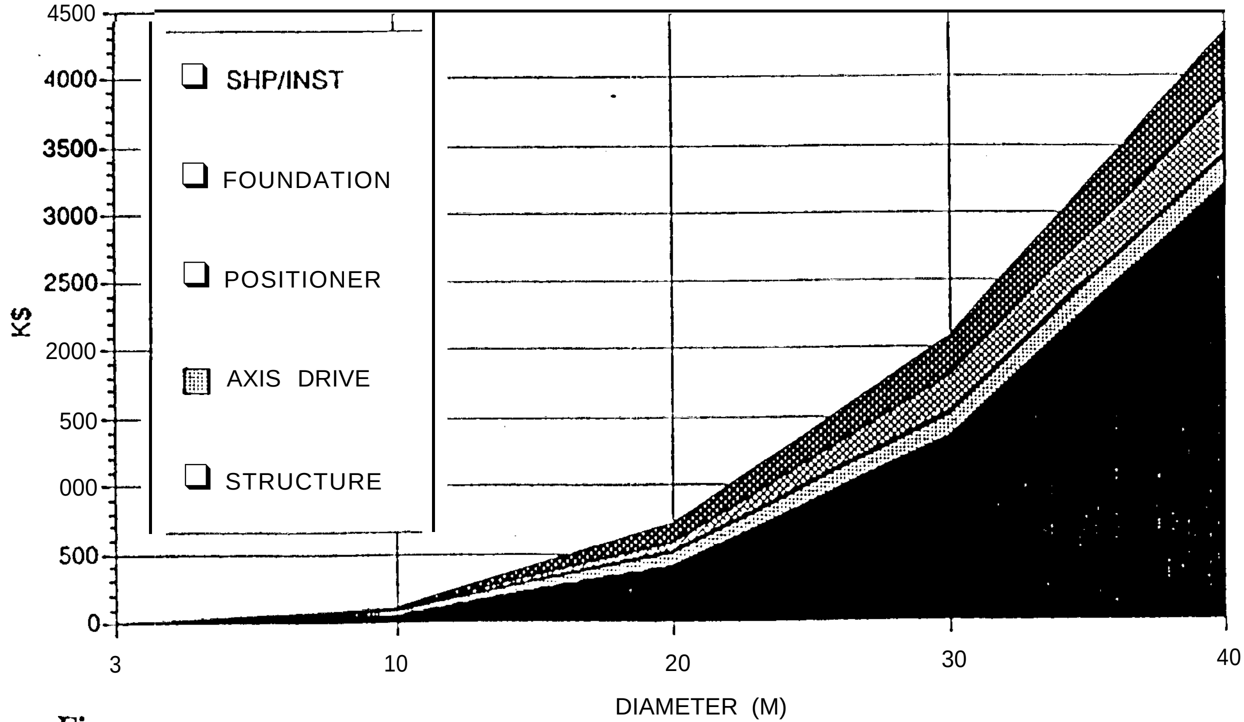


Figure 3. Cost Breakdown for Typical **Reflector Antenna Systems by Category**

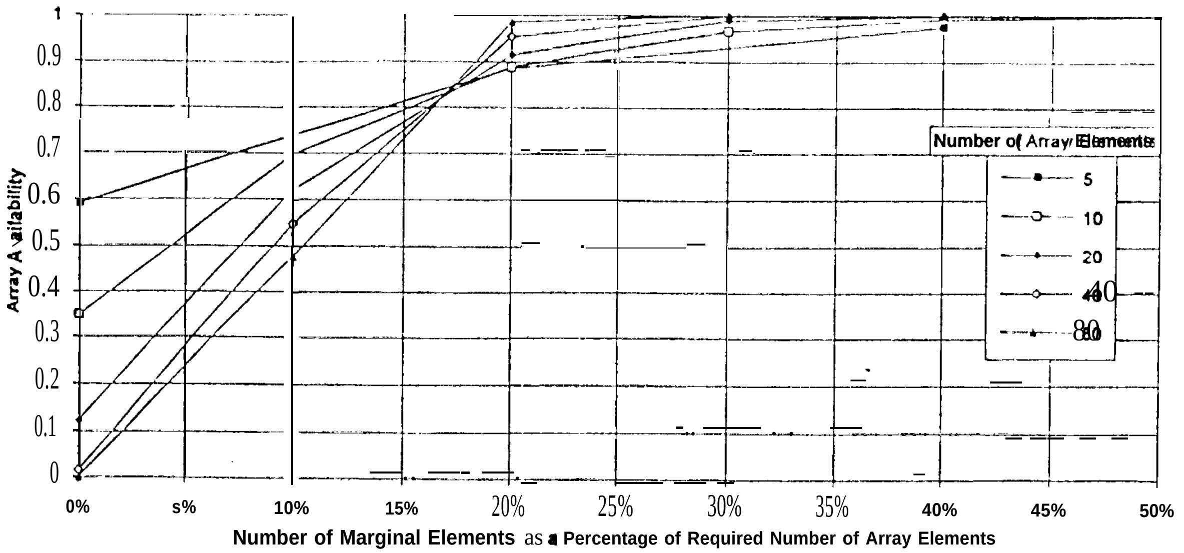


Figure 4. Array Availability for a Given Number of Elements, as a Function of Number of Additional Marginal Elements

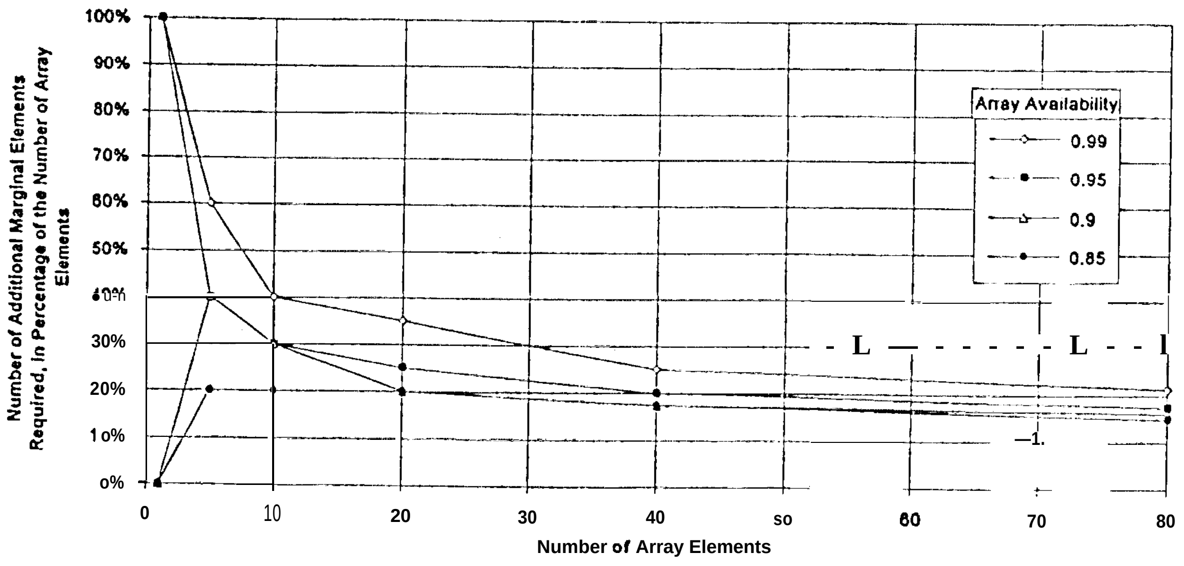


Figure 5. Number of Additional Marginal Elements Required for given Array Availability, as a function of Number of Array Elements
Assumed Element Availability: 0.9

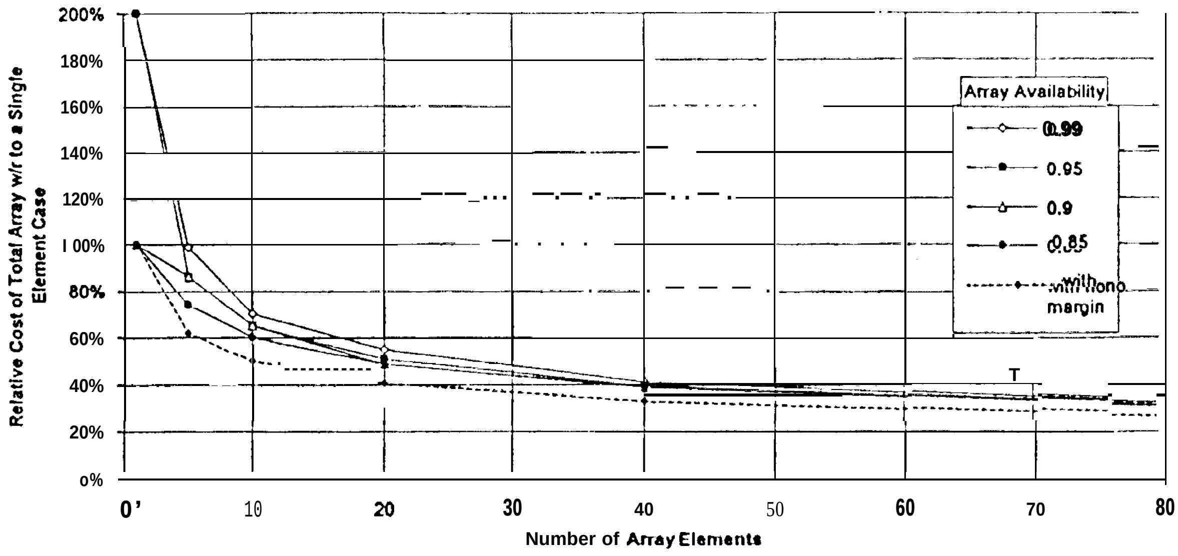


Figure 6. Relative Cost of Total Array with Required Marginal Elements for Given Array Availability, as a Function of Minimum Number of Array Elements
Assumed Element Availability: 0.9

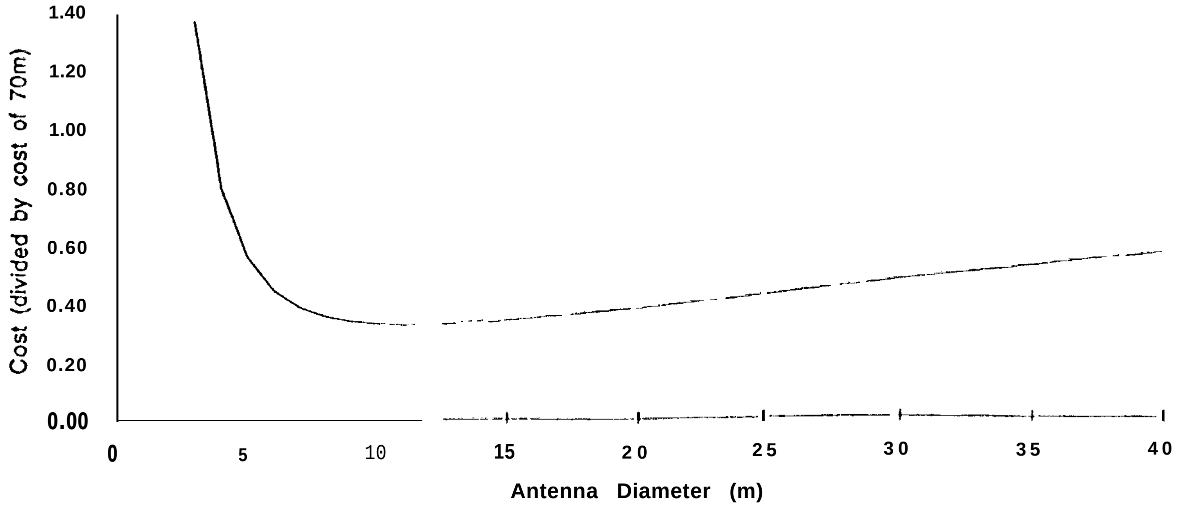


Figure 7. A Preliminary Model for Total Reflector Array System Cost (including receiver, correlator, combiner, etc.), Versus Antenna Diameter